The 2009 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 11-15, 2009 St. Louis, USA

Haptic Device Using Flexible Sheet and Air Jet for Presenting Virtual Lumps under Skin

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Abstract—**A haptic device using flexible sheet and air jet is proposed. This device presents haptic sensation of virtual lumps under skin to user's finger. A tensioned flexible sheet is regarded as virtual skin. A user touches the sheet directly with his finger. Then he feels the softness of normal skin as the sheet compliance. A nozzle fires thin beam of air jet to the sheet from its back, when the user touches the sheet at the location of a virtual lump. The fingertip feels the small hard part made by the air jet through the sheet. This can be the virtual lump. In order to present multiple virtual lumps, the nozzle is attached to a manipulator. A camera measures the fingertip motion, and the manipulator moves the nozzle together with the fingertip. The nozzle fires the air jet when the fingertip is on the virtual lumps. We can vary the hardness of a virtual lump by controlling the flow rate of air. We can also vary the size of the virtual lump by controlling the distance between the nozzle and the sheet; the shorter distance makes the virtual lump smaller. This is because the air jet radiates out from the nozzle. Some experiments of presenting multiple virtual lumps and varying the hardness and size of a virtual lump are performed.**

I. Introduction

In some virtual reality applications, it is important to present haptic sense when users touch virtual objects. Devices presenting virtual haptic sense are called haptic devices or haptic displays[1-10]. One medical application of haptic devices is a training simulator of doctors. A haptic device simulates haptic sense in medical practices such as palpation and surgery and presents the simulated haptic sense to trainees. In this application, it is necessary that doctors can feel like treating real patients: they can touch virtual patients' bodies directly with their hands or fingers, and their movement is not restricted. Virtual objects presented in the medical field are bodies and organs, which are soft and flexible. Hence haptic devices for presenting virtual soft objects are required.

We already proposed a haptic device using flexible sheet; it enables users to feel like pushing virtual soft objects directly with their fingers[11-14]. This device varies sheet compliance in the normal direction by changing the bias tension applied to the sheet: tightly stretched sheet feels hard, and loose sheet feels soft. When a user pushes the sheet with his finger, he can feel the softness of virtual objects as the sheet compliance. This device applies the bias tension to the sheet by pulling four corners of the sheet with actuators. Hence we only control the whole compliance of the sheet. We cannot generate different compliance with location (i.e. soft area and hard area) in the sheet.

Now we consider lumps under skin. A small hard part exists under skin, and a human detect the lump by stroking or pushing this part with his finger or palm. In order to simulate the haptic sense in the above-mentioned palpation with a haptic device, the device needs to present a wide soft surface and a small hard area (or point) inside the wide surface. The wide surface corresponds to virtual skin, and the small area to a virtual lump. The hardness and size of the small area must be variable. A user touches the device directly with his finger or palm. Most of conventional haptic devices which present surface texture or asperity and are touched directly with fingers use dense array of pins, each of which runs out and in. This mechanism cannot generate wide and smooth surface. In order to generate different compliance with location, each pin must be controlled by force control. That requires at least one actuator and one force sensor for each pin; thus the system becomes complex and huge.

In the present study we propose a haptic device using flexible sheet and air jet. The objective of the device is a palpation simulator for the training of the detection of lumps under skin. This device presents haptic sensation of virtual lumps under skin to user's finger. First a tensioned flexible sheet is regarded as virtual skin. It provides a user with a wide and smooth surface. The user touches the sheet directly with his finger. Then he feels the softness of normal skin as the sheet compliance. Second a nozzle fires thin beam of air jet to the sheet from its back, when the user touches the sheet at the location of a virtual lump. The fingertip feels a small hard part which is locally generated by the air jet through the sheet. This can be the virtual lump. In order to present multiple virtual lumps, the nozzle is attached to a manipulator. A camera measures the fingertip motion, and the manipulator moves the nozzle together with the fingertip. The nozzle fires the air jet when the fingertip is on the virtual lumps. We can vary the hardness of a virtual lump by controlling the flow rate of air. We can also vary the size of the virtual lump by controlling the distance between the nozzle and the sheet; the shorter distance makes the virtual lump smaller. This is because the air jet radiates out from the nozzle. Some experiments of presenting multiple virtual lumps and varying the hardness and size of a virtual lump are performed.

Manuscript received March 1, 2009.
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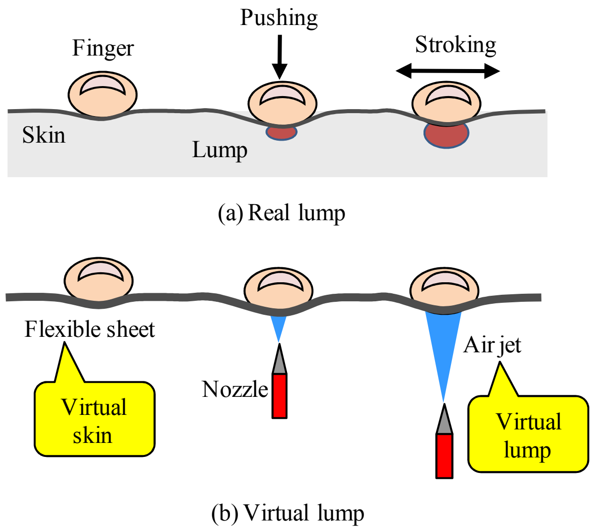


Fig.1 Haptic device presenting virtual lumps using flexible sheet and air jet

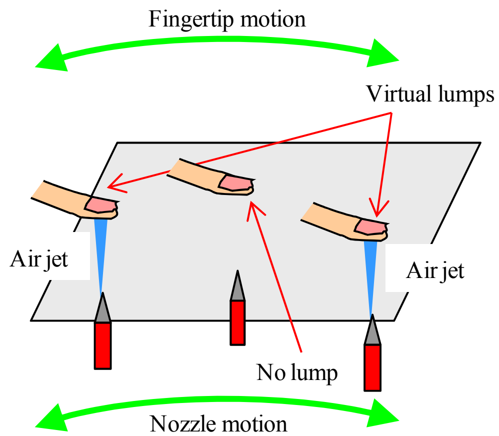


Fig.2 Presenting multiple virtual lumps by moving nozzle of air jet

II. Haptic Device Using Flexible Sheet and Air Jet

A. Method of Presenting Virtual Lumps under Skin

The objective of this study is to develop a haptic device which simulates haptic sensation of lumps under skin. Fig.1(a) shows actual situation of feeling a lump under skin with a finger. When the fingertip pushes the area without lumps, it feels the softness of normal skin. When the fingertip pushes or strokes the location of the lump, it feels a small hard part under the skin. Fig.1(b) shows our proposed method of simulating this situation artificially. A tensioned flexible sheet is regarded as virtual skin. A nozzle fires thin beam of air jet to the sheet from its back, thus generating a small hard part on the sheet. This can be a virtual lump.

(1) When the fingertip is away from the sheet or pushes the area without virtual lumps, the nozzle does not fire the air jet. Then the fingertip pushing the sheet feels the softness of normal skin as the sheet compliance.

(2) When the fingertip pushes or strokes the location of a virtual lump, the nozzle fires the air jet. Then the fingertip feels the hard lump made by the air jet through the sheet.

(3) When the location of the virtual lump is changed or multiple virtual lumps exist, we move the nozzle so that it can always face the fingertip across the sheet. Then the nozzle fires the air jet only when the fingertip comes on the virtual lumps (Fig.2).

(4) We vary the hardness of the virtual lump by controlling the flow rate of air jet, Q. The more flow rate Q applies the larger force to the finger through the sheet. Hence the finger feels the harder lump.

(5) We control the distance between the nozzle and the sheet, L, to vary the size of the virtual lump. The air jet radiates out from the nozzle. As the distance L becomes shorter, the area where the air jet attacks is narrower. It means that the virtual lump becomes smaller (Fig.3).

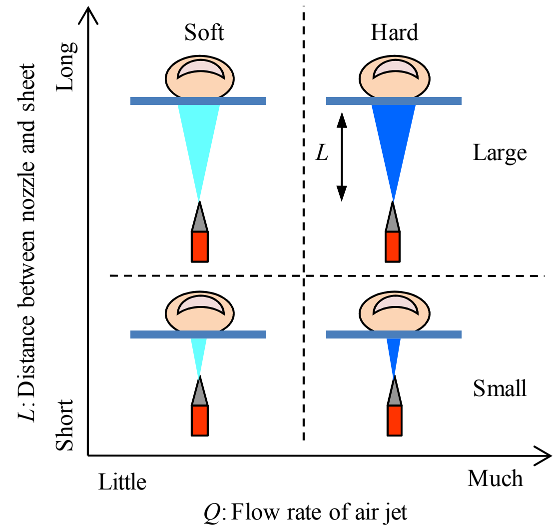


Fig.3 Varying hardness and size of virtual lump by controlling flow rate of air jet and distance between nozzle and sheet

B. Prototype Device for Experiments

Fig.4 shows the prototype device used in experiments. The sheet is made of silicon rubber. It is attached to a frame, whose size is 220[mm]x170[mm]. The sheet's thickness is 0.5[mm]. Because the experiments in this study are mainly focused on the generation of virtual bumps by air jet, the sheet is strained at constant tension.

Fig.5 shows the air jet control system. The air from the compressor goes through the regulator, thus its pressure becomes constant. In the following experiments, the constant pressure is 0.3[MPa]. This air is sent to the proportional control valve KFPV050 (KOGANEI Corporation). The proportional control valve controls the flow rate of the output air, Q, in proportion to electric signals (voltage), which is given by the computer through the D/A converter of 12 bit. The controlled air is sent to the jet nozzle SPN301 (Sanwa

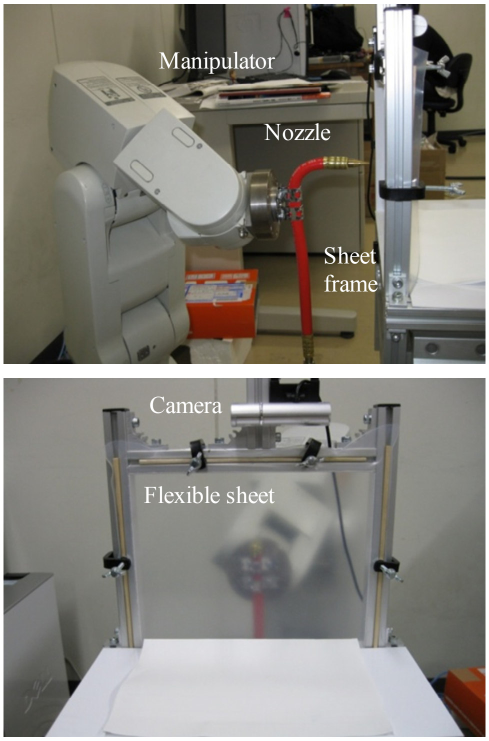


Fig.4 Experimental system of haptic device using flexible sheet and air jet

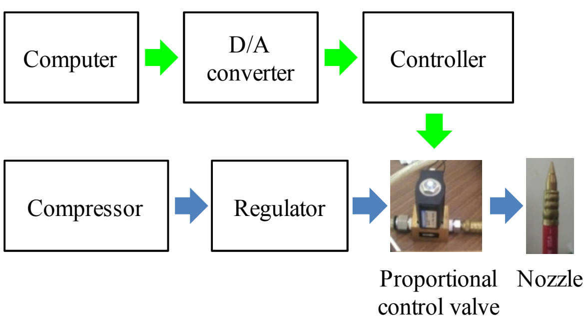
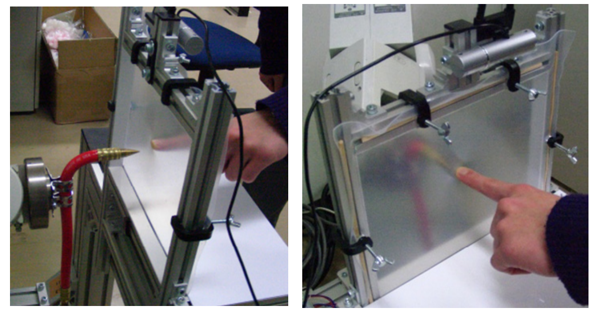


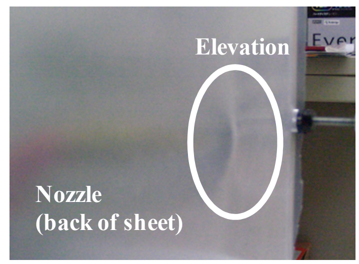
Fig.5 Air jet control system

Enterprise Co., Ltd.). Because we cannot measure the flow rate of the output air jet directly, we express the flow rate Q by the commanded value (0 to 4095) to the D/A converter.

We use a camera to measure the fingertip position. The color USB camera offers 1.3 million pixels. The image obtained by the camera is binarized. Because the background scene from the camera is white and a black mark is attached to the nail, we can extract the nail area from the binary image; the nail area is black and the other area is white. Then the nearest position of the nail area to the sheet gives the fingertip position. The coefficient between the length in the camera image and the length in the real world is measured beforehand. In the following experiments, this coefficient is 0.188[mm/pixel]. Currently we attach one camera on the top of the sheet frame (Fig.4). Thus it can measure the horizontal position x and the position perpendicular to the sheet, z. The



(a) Fingertip touching virtual lump



(b) Elevation made by air jet

Fig.6 Fingertip touching virtual lump

position z is the distance between the fingertip and the sheet when the fingertip is away from the sheet; it is the indentation of the sheet when the fingertip touches the sheet. We can also attach another camera to the side of the sheet frame to measure the vertical position y. Then the fingertip can move around in x and y directions. We can easily revise the current method to this case.

The nozzle is attached to and moved by the 6-DOF manipulator RV-1A (Mitsubishi Electric Corporation). The fingertip position in the camera image is converted to the position in the real world, and the manipulator moves the nozzle so that the nozzle can always face the fingertip across the sheet. The sampling time for one control loop is 0.07[s]. Currently we use the 6-DOF manipulator to move the nozzle. But we only need to move 3-DOF position of the nozzle. Thus the manipulator can be replaced by a simpler and smaller mechanism such as an XYZ stage. Then the device will be much more compact and cheaper than the current one.

Fig.6(a) shows the fingertip touching a virtual lump. The nozzle faces the fingertip across the sheet and fires the air jet. In order to help you understand, Fig.6(b) shows the air jet blowing on the sheet without fingertips. A sharp elevation made by the air jet appears in the surface of the sheet. Actually a fingertip compresses this elevation, thus feeling a virtual lump.

C. Features

(1) The proposed device presents haptic sensation of virtual lumps under skin to user's finger.

(2) It provides the user with two kinds of softness: a wide soft surface as virtual skin and a small hard area (or point) as a virtual lump inside the wide surface.

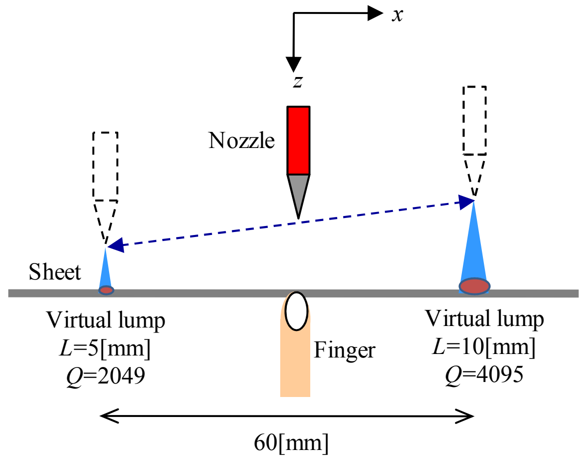
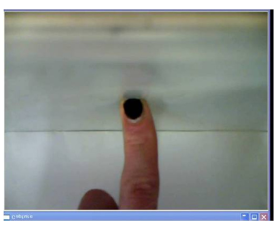
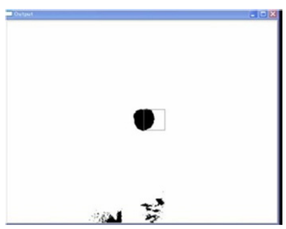


Fig.7 Experiment of presenting two virtual lumps



(a) Color image



(b) Binary image

Fig.8 Measurement of fingertip position using camera

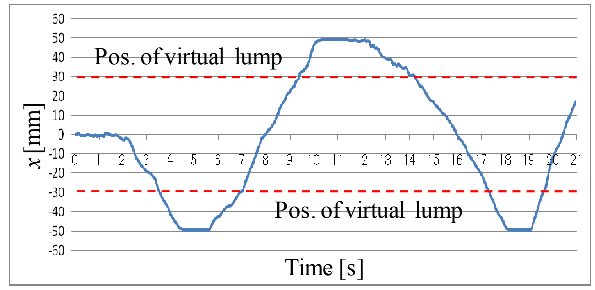
(3) A tensioned flexible sheet is regarded as virtual skin. The beam of air jet generates the virtual lump.
(4) The user touches the device directly with his finger and feels the softness.
(5) The hardness and size of the virtual lump are variable.
(6) Compared with conventional haptic devices using dense array of pins, the mechanism and control method of the proposed device are simple. Replacing the 6-DOF manipulator of the current device with an XYZ stage makes the device much more compact.

III. EXPERIMENT OF PRESENTING MULTIPLE VIRTUAL LUMPS

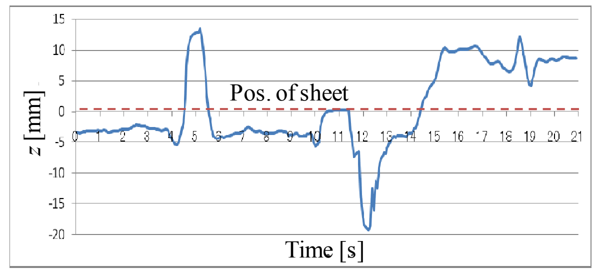
A. Experimental Method

The first experiment is on the presentation of multiple virtual lumps. Fig.7 illustrates the sheet seen from above. We set two virtual lumps on the different points of the sheet. The lumps exist at the same level, and the distance between them is 60[mm]. For the left virtual lump, the distance between the nozzle and the sheet, L, is 5[mm] and the commanded value of the flow rate of the air jet, Q, is 2049. For the right virtual lump, L=10[mm] and Q=4095. The horizontal direction is x-axis, and the direction perpendicular to the sheet is z-axis.

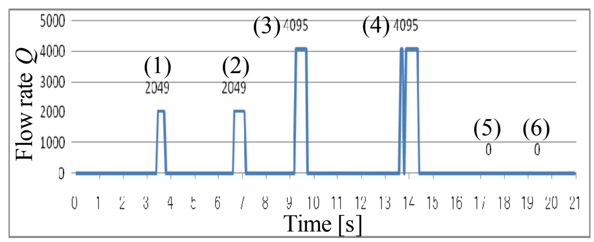
A finger moves left and right in horizontal direction with/without touching the sheet. The fingertip position is measured by the camera, and the manipulator moves the nozzle so that



(a) x-position of fingertip



(b) z-position of fingertip



(c) Q: Flow rate of air jet (commanded value)

Fig.9 Experimental results of presentation of two virtual lumps

the nozzle can always face the fingertip across the sheet. As shown in Fig.7, the nozzle moves along the straight line between the left and right virtual lumps. The nozzle fires the air jet only when the fingertip comes on the virtual lump and touches the sheet.

B. Experimental Result

Fig.8 shows the experimental result of the measurement of the fingertip position: (a) the color image obtained by the camera, and (b) its binary image. In the color image, the horizontal line near the center is the boundary between the sheet and the background white board. The upper area is the sheet. A black mark is attached to the nail. By setting the appropriate threshold for binarization, we can extract the black nail area from the binary image. The top of the black area is regarded as the fingertip position.

Fig.9 shows the experimental result: (a) the x-position of the fingertip measured by the camera, (b) the z-position of the fingertip, and (c) the commanded value of the flow rate of the air jet, Q, which is the input to the D/A converter. The x-position of the fingertip shows the horizontal movement along the sheet. The dotted lines represent the positions of the two virtual lumps. The fingertip moves left and right in

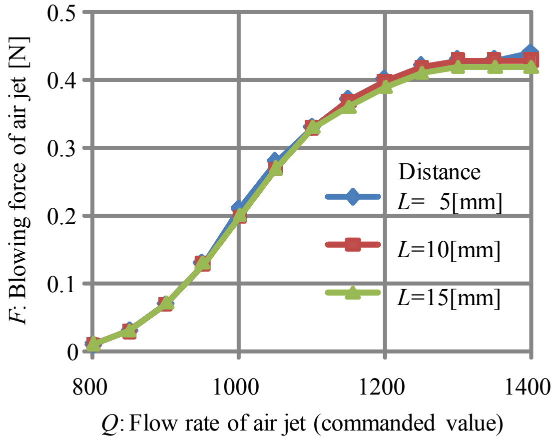


Fig.10 Experimental results of blowing force of air jet

(a) L=5[mm] (b) L=15[mm]

Fig.11 Experimental results of camera images of area depressed by air jet blowing on back of hand

horizontal direction beyond the virtual lumps. The z-position of the fingertip shows the movement in the direction perpendicular to the sheet. The dotted line represents the position of the sheet surface. If the z-position is less than this line, the fingertip touches the sheet. Otherwise the sheet is away from the sheet.

From the moments of firing the air jet shown in Fig.9(c) and the corresponding (x, z) position of the fingertip shown in Fig.9(a)(b), we obtain the following results:

(1)(2) The nozzle fires the air jet of Q=2049 when the fingertip moves across the left virtual lump while touching the sheet.

(3)(4) The nozzle fires the air jet of Q=4095 when the fingertip moves across the right virtual lump while touching the sheet.

(5)(6) The nozzle does not fire the air jet because the fingertip moves across the left virtual lump but does not touch the sheet.

Because the objective of the proposed haptic device is virtual palpation for detecting lumps, the fingertip moves slowly. Thus the manipulator moves the nozzle so that the nozzle can always follow the fingertip position measured by the camera. If the fingertip must be moved faster, we need to apply the control method for encountered-type haptic devices to our device: the device is prepared at the point of the virtual lump before the fingertip reaches this point.

IV. Experiment of Varying Hardness and Size of Virtual Lump

A. Experimental Method

We tested how the hardness and size of a virtual lump vary when the distance between the nozzle and the sheet, L, and the flow rate of air jet, Q, are changed.

First we measure the blowing force of the air jet, F, when the distance L and the flow rate Q are different. The force gauge ZPS-DPU-20N (IMADA Co., Ltd.) is placed in front of the nozzle. The air jet blows on the sensor head (load cell) of the gauge; the force F[N] is measured. The resolution of the gauge is 0.01[N]. The area of the circular sensor head is 13.7[mm^2]. The commanded value of the flow rate, Q, is changed in the range of 800 to 1400. The distance between the nozzle and the sensor head, L, is set to 5, 10 and 15[mm].

Second we observe the size of the area depressed by the air jet when the distance L is different. The air jet blows on the back of the hand, and we take pictures of the depressed area with a camera. The commanded value of the flow rate, Q, is set to 2000. The distance between the nozzle and the back of the hand, L, are 5 and 15[mm].

B. Experimental Result

Fig.10 shows the measured blowing force of the air jet. As the commanded value of the flow rate, Q, increases, the blowing force F increases. The relationship between Q and F is nonlinear. F is saturated when Q is greater than 1300. The Q-F curves are almost the same when the distance between the nozzle and the sensor head, L, changes in the range of 5 to 15[mm].

Fig.11 shows the camera images of the depressed area when the air jet blows on the back of the hand. You can see that the depressed area is larger when the distance between the nozzle and the back of the hand, L, is longer. After the air jet hits the back of the hand, it radiates sideward and enlarges the depressed area. Thus the area on which the air jet blows directly is smaller than the depressed area you see in these pictures.

Accordingly we can vary the hardness and size of virtual lumps by changing the flow rate of the air jet, Q, and the distance between the nozzle and the sheet, L.

V. Conclusion

We proposed a haptic device using flexible sheet and air jet. This device presents haptic sensation of virtual lumps under skin to user's finger. It provides the user with two kinds of softness: a wide soft surface as virtual skin and a small hard area (or point) as a virtual lump inside the wide surface. A tensioned flexible sheet is regarded as virtual skin. The beam of air jet generates the virtual lump. The hardness and size of the virtual lump are variable. The user touches the device directly with his finger and feels like pushing or stroking the virtual lumps under skin. As the experimental results, we could present two virtual lumps at different points on the sheet. We ascertained that we can vary the hardness and size of virtual lumps by changing the flow rate of the air jet and the distance between the nozzle and the sheet.

In future works we will revise the device smaller and perform subjective evaluation on the presentation of virtual lumps compared with real lumps, especially on the difference in the hardness and size of virtual lumps.

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